ISOSTATIC RESIDUAL GRAVITY ANOMALY MAP OF THE PALO ALTO 7.5' QUADRANGLE, CALIFORNIA Steven F. Carle and V. E. Langenheim

# PRELIMINARY GROUND WATER QUALITY DATA AND THE EXTENT OF THE GROUND WATER BASIN FROM DRILL HOLE, SEISMIC, AND GRAVITY DATA IN THE PALO ALTO 7.5' QUADRANGLE, CALIFORNIA

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EXPLANATION

Contours of residual gravity. Contour interval 0.5 mGal Barbed lines enclose areas of low residual gravity.

Gravity station collected by USGS, March-July 1989.

Gravity station collected by others.

#### INTRODUCTION

A gravity study was conducted by the U.S. Geological Survey as part of a request by the City of Menlo Park to help determine the location and quantity of groundwater. The study area includes Menlo Park, Atherton, and Menlo Park Municipal Water District land. New gravity measurements were made primarily in the study area, but additional gravity measurements were made in adjoining areas in East Palo Alto, Palo Alto, Redwood City, Woodside, and adjacent unincorporated areas to improve regional coverage near the study area. Regional gravity coverage was supplemented with gravity measurements by C. W. Roberts (written communication, 1989) and a compilation by Robbins and others (1978) of previous gravity measurements. An isostatic residual gravity anomaly map was compiled for the Palo Alto 7.5' quadrangle, California, which includes the study area and adjoining areas.

In general, isostatic residual gravity anomalies are caused by lateral density variations within the shallow crust. Bedrock is defined in this study to be rocks older than the Santa Clara Formation (upper Pliocene and lower Pleistocene). All the unconsolidated to weakly consolidated sedimentary rocks younger and including the Santa Clara Formation are collectively referred to as "alluvial deposits." In the Palo Alto 7.5' quadrangle, some of the significant lateral density variations are related to (1) variations in thickness and lateral variations in density of the Tertiary (pre-late Pliocene) sedimentary and volcanic sequence, (2) variations in rock type within the Franciscan assemblage (Jurassic and Cretaceous) and (3) variations in thickness of unconsolidated to weakly consolidated sedimentary deposits younger than and including the upper Pliocene and lower Pleistocene Santa Clara Formation (Brabb and Pampeyan, 1983). These sedimentary deposits mainly consist of alluvial deposits and lesser amounts of stream terrace deposits and bay mud, all of which are generally referred to as "alluvial deposits" in this report. The alluvial deposits contain most of the available ground water and constitute the "ground water basin" (Barrett Consulting

The main purpose of the gravity study was to determine the elevation of the bottom of the ground water basin, equivalent to the buried bedrock surface (see Sheet 3), which is determined by subtracting the thickness of alluvial deposits from the land surface elevation. Another purpose of the gravity study was to detect any other structures, such as faults or contacts, that might affect ground water movement. Density measurements of bedrock samples and a borehole gravity survey through alluvial deposits assisted interpretation of gravity

Group, 1989).

#### COLLECTION AND REDUCTION OF GRAVITY DATA

The gravity data consist of 398 new stations measured in March-July 1989 and 136 old stations consisting of a compilation by Robbins and others (1978) and measurements on the Dumbarton Bridge and approach by C. W. Roberts (written communication, 1989). The principal facts for the new data are available on IBM diskette (Carle and Langenheim, 1989). Most of the new gravity stations are located within the study area where a spacing of within 400 m (1/4 mile) was attempted. The 400 m spacing could not always be achieved on private property, the salt evaporators, and marshlands due to access problems. New stations outside the study area provide regional gravity coverage.

the new gravity measurements. The observed gravity values were referenced to the International Gravity Standardization Net 1971 (IGSN71) gravity datum (Morelli, 1974). All gravity measurements were made relative to base station MPA (Menlo Park A) assuming linear meter drift between base readings. The following corrections were applied to the observed gravity values to obtain isostatic residual gravity values:

Lacoste and Romberg gravity meters G-8 and G-614 were used for all of

for the gravitational force of and the solid-earth tidal response to the sun and moon; for the variation of gravity with latitude for the decrease of gravity away from the center of the free-air

for the gravitational effect of the mass between the station Bouguer and sea-level: for curvature of the earth;

for the gravitational effect of topography; for the long-wavelength gravitational effect of isostatic compensation of the crust due to topographic loading. The earth tide correction was computed from formulas by Longman (1959).

The latitude and free-air corrections were made according to the Geodetic Reference System of 1967 (International Union of Geodesy and Geophysics, 1971). The Bouguer, curvature, and outer-zone (beyond 590 m) terrain corrections were determined by a computer procedure by Godson and Plouff (1988). The isostatic correction was computed by the program ISOCOMP (Jachens and Roberts,

A terrain density of 2.67 g/cm<sup>3</sup> was assumed for the terrain and Bouguer corrections. The Hayford-Bowie (1912) system was used for the inner-zone terrain correction within 590 m. For the A and B zones, the terrain correction was estimated in the field. For the C and D zones, compartment elevations were automatically estimated by computer using a digital elevation model (DEM) with 30 m grid spacing. This was accomplished by averaging the DEM elevation values located within each Hayford-Bowie compartment. For improved accuracy, C1, C2, D1, and D2 subcompartments (Spielman and Ponce, 1984) were used. With 30 m spacing, about 5 DEM elevation values are averaged in the smallest (C1) subcompartments to obtain the estimate of the compartment elevation.

For the isostatic correction, an Airy-Heiskanen model (Heiskanen and Vening Meinesz, 1958) with a sea-level crustal thickness of 25 km, a crust-mantle density contrast of 0.40 g/cm<sup>3</sup>, and density of 2.67 g/cm<sup>3</sup> for the topographic load was assumed. Elevations of gravity stations were determined from bench marks, spot elevations, and contour interpolation from the U.S. Geological Survey Palo Alto 7.5' topographic quadrangle map (20 ft contours with 5 ft supplemental contours) and additional maps by the County of San Mateo and the City of Meulo Park (1, 5 and 20 ft contours). For most stations, the isostatic

## DENSITY MEASUREMENTS

residual gravity values are expected to be accurate to within 0.2 mGal.

Density measurements were performed on twelve rock samples collected by the authors and 147 rock samples collected by E. H. Pampeyan in 1962-4 in connection with geologic mapping of the Palo Alto 7.5' quadrangle (Pampeyan, 1970). The saturated bulk density, hereafter referred to as "density", of rock samples was measured using the buoyancy method (see Table 1). Average density values were determined for each rock type, and these values were later used for interpretation and gravity modeling (Sheet 3). Lithic materials exposed within the Palo Alto 7.5' quadrangle can be divided into three main rock units according to age, lithology, and density: (1) the Jurassic and Cretaceous Franciscan assemblage (2.67 g/cm3), (2) Tertiary (pre-late Phiocene) sedimentary and volcanic sequence (2.36 g/cm<sup>3</sup>), and (3) upper Pliocene and Quaternary alluvial deposits  $(2.12 \text{ g/cm}^3)$ .

The Franciscan assemblage in this area consists mostly of greenstone and graywacke with lesser amounts of chert, serpentinite, limestone and exotic "clasts," such as blueschist (Brabb and Pampeyan, 1983). The graywacke is generally well-indurated, moderately to poorly sorted, dark gray to green sandstone with interbedded siltstone and shale. It appears to have undergone incipient metamorphism (prehnite-pumpellyite assemblage, sutured grain contacts, etc.). The densities of 28 graywacke samples range from 2.34 to 3.10 g/cm<sup>3</sup>, averaging 2.63 g/cm<sup>3</sup>. Chert and limestone of the Franciscan assemblage have similar densities, averaging about 2.60 and 2.65 g/cm<sup>3</sup>, respectively. One chert sample has an anomalously low density (1.86 g/cm<sup>3</sup>), but it is extremely brecciated and altered and therefore was not included in determining the unit's average density. Franciscan greenstones are generally massive. They may be vesicular and may contain localized calcite veins. Greenstone densities range from 2.49 (altered) to 3.06 g/cm<sup>3</sup>, with an average of 2.82 g/cm<sup>3</sup>. Serpentinite bodies within the Franciscan assemblage are very heterogeneous in texture and composition. The heterogeneity is reflected in the densities which range from 1.81 g/cm<sup>3</sup> (waxy layered clay) to as high as 3.40 g/cm<sup>3</sup> (containing chromite). The average serpentinite density, in any case, is 2.32 ± 0.20 g/cm<sup>3</sup>. If one ignores the densities of very weathered serpentinite masses (less than 2.00 g/cm<sup>3</sup>), the average density for these bodies at depth is about 2.47 g/cm<sup>3</sup>. Blocks of blueschist are often associated with the serpentinite bodies (Brabb and Pampeyan, 1983); they are characterized by high densities, from 2.90 to 3.08 g/cm<sup>3</sup>. These exotic blocks are generally small (commonly less than 3 m in diameter) and therefore probably do not contribute significantly to the overall density of the Franciscan assemblage. In summary, the overall density of this very heterogeneous collage of lithologies is about 2.67 g/cm<sup>3</sup>, assuming that the Franciscan assemblage consists of 65% graywacke, 25% greenstone, 5% serpentinite, and 5% chert and limestone (percentage based on our estimate of the composition of the Franciscan assemblage as mapped by Pampeyan, 1970). Moreover, gravity measurements taken over terrain underlain by the Franciscan in central California which were reduced for a range of densities between 2.4-2.8 g/cm3, indicated that, in general, a reduction density of 2.67 g/cm<sup>3</sup> minimizes the correlation between gravity anomalies

and topography (Robbins and others, 1977). The Tertiary (pre-late Pliocene) sedimentary and volcanic sequence, hereafter referred to as the Tertiary sequence, consists of Eocene and Miocene sandstone, shale, and conglomerate and Miocene volcanic rocks. We have divided the Tertiary sequence into three parts: (1) Eocene sandstones and shales (Butano? Sandstone), (2) Miocene sandstones and shales (unnamed sandstone and Monterey Formation), and (3) early or middle Miocene basalt (Page Mill Basalt). The Eocene sandstones are generally arkosic and of varying induration. They are glauconitic and conglomeratic in places. Densities range from 1.90 to 2.72 (greenstone conglomerate) g/cm<sup>3</sup>, with an average of about 2.44 g/cm<sup>3</sup>. The Miocene sedimentary rocks are characterized by a somewhat lower average density (2.28 g/cm<sup>3</sup>). Lithologies measured are mostly siltstones and poorly cemented sandstones, but also include coquina and chert-lithic quartzites. The range in densities is large, 1.59 to 2.91 g/cm<sup>3</sup>. The Page Mill Basalt ranges from 2.05 (very weathered) to 2.99 (very fresh and massive) g/cm<sup>3</sup>. In conclusion, we would assign an average density of 2.36 g/cm<sup>3</sup> to the Tertiary (pre-late Pliocene) formations, noting that the Page Mill Basalt is thin or nonexistent throughout much of the Palo Alto 7.5' quadrangle (Brabb and Pampeyan, 1983)

We did not measure any densities from the alluvial deposits and the Pliocene and Pleistocene Santa Clara Formation, but density data are published for various Quaternary lithic units in San Mateo County (Lajoie et al., 1974). From these data, an average density of the alluvial deposits is around 1.8 to 2.0 g/cm<sup>3</sup> depending greatly on the degree of consolidation (none to weak) and proportion of gravel, sand, and clay. Beyer (1980) used borehole gravity to determine densities of alluvial deposits in situ with respect to depth at the NASA-Ames Research Center well (#10-1) in Mountain View. This well was also logged for self-potential. The uppermost 1,000 feet (303 m) has an average density of around 2.12 g/cm<sup>3</sup> whereas below this level, the density is somewhat greater, about 2.25 g/cm<sup>3</sup>. The average density of the 1,340 feet (409 m) of measured

section is about 2.16 g/cm<sup>3</sup>. The bottom 200 feet (61 m) of the measured interval may actually be Tertiary sedimentary rocks rather than Quaternary alluvial deposits because of greater activity shown on the spontaneous potential log of the well, but this activity can also be attributed to higher-salinity waters within the Quaternary alluvial deposits, which have been found in other deep wells (Department of Water Resources, 1967). The well penetrated Franciscan rocks at about 1390 feet (424 m) according to the electric logs. Unfortunately, there is no lithologic log for this well. Using methods other than borehole gravity, the sample may be disturbed or taken at depths too shallow to represent the overall column of the alluvial deposits. Borehole gravity is a direct method for determining in situ bulk density. The 0 to 1000 feet depth range of the borehole gravity survey should be representative of the alluvial deposits in the Palo Alto 7.5' quadrangle, where the alluvial deposits are usually less than 1000 feet thick. In conclusion, we assign a density of 2.12 g/cm<sup>3</sup> for the alluvial deposits based on the borehole gravity survey (Beyer, 1980).

Our density measurements compare favorably with previous measurements of surface samples of the Franciscan assemblage, Tertiary sequence, and alluvial deposits in the San Francisco Bay area. Robbins (1971) found average densities of 2.7 g/cm<sup>3</sup> for Franciscan sedimentary rocks, 2.5 g/cm<sup>3</sup> for Franciscan serpentinites and 2.8 g/cm<sup>3</sup> for Franciscan greenstones. For the Tertiary (pre-late Pliocene) marine deposits, he used an average of 2.3 g/cm<sup>3</sup>. His average densities for the Quaternary alluvial deposits and Pliocene and Pleistocene Santa Clara Formation are 1.9 g/cm<sup>3</sup> and 2.2 g/cm<sup>3</sup>, respectively.

Although our density measurements from surficial rock samples probably are somewhat lower than for the densities of rocks at depth, we are more in terested in density contrasts rather than absolute numbers for the purpose of gravity modeling. Thus, the average density contrast between the alluvial deposits and the Franciscan assemblage is about -0.55 g/cm<sup>3</sup>; the contrast between the alluvial deposits and the Tertiary sequence is smaller, about -0.24 g/cm<sup>3</sup>; and the average density contrast between the Tertiary sequence and the Franciscan rocks is about -0.31 g/cm<sup>3</sup>. There are important density contrasts within the Franciscan assemblage. Greenstone within the Franciscan assemblage exhibits a positive density contrast relative to the dominant graywacke of about +0.19 g/cm<sup>3</sup>, whereas serpentinite exhibits a density contrast of about -0.16 g/cm<sup>3</sup>

#### INTERPRETATION

The isostatic residual gravity anomalies in the Palo Alto 7.5' quadrangle are caused mainly by variations in thickness of alluvial deposits and the Tertiary sequence and variations in density in the various lithologies within the Franciscan assemblage. The average density of 2.67 g/cm<sup>3</sup> for the Franciscan assemblage will more often be referred to because the specific lithic composition of the Franciscan assemblage where concealed is not well known. In general, rock units tend to extend further horizontally than vertically. As an approximation, gravity anomalies may then be interpreted relative to the limiting case, the gravitationa effect of an infinite or "Bouguer" slab,

where  $\Delta \rho$  is the density contrast, G is the universal gravitational constant, and

t is the thickness of the slab. Then an approximation of the residual gravity effect of alluvial deposits overlying the Franciscan assemblage is -0.70 mGal per 100 feet (30 m) of alluvial deposits, assuming a density contrast of -0.55 g/cm The Bouguer slab relationship is a good approximation for the alluvial de posits, which are usually flat lying and typically extend 10 to 100 times greater laterally than vertically. For example, the gravitational effect of a flat lying layer where the lateral extent is 10 times the thickness is 95% of a Bouguer slat Where alluvial deposits overlie Tertiary rocks (-0.24 g/cm<sup>3</sup> density contrast). the residual gravity effect is approximately -0.31 mGal per 100 feet thickness of alluvial deposits, and where the Tertiary (pre-late Pliocene) sedimentary sequence overlies the Franciscan assemblage (-0.31 g/cm<sup>3</sup> density contrast) the residual gravity effect is approximately -0.39 mGal per 100 feet of the Tertiary sequence. However, the Tertiary sequence is generally not flat lying, but highly folded and faulted, with a thickness of a few thousand feet and a width of a few miles. Therefore, the Bouguer slab approximation is not as good for the Tertiary sequence, and, therefore, should be considered more of a limiting case. These ratios of gravity effect per unit thickness generally explain the isostatic residual gravity anomalies on the Palo Alto 7.5' quadrangle.

The isostatic residual gravity anomalies range from less than -14 mGal to about +11 mGal. The largest positive anomalies occur over the exposed or thinly covered parts of the Franciscan assemblage, as expected for these high density rocks. These gravity highs occur northwest of Eagle Hill in Redwood City (+9 near Portola Valley (+10 to +11 mGal). Relatively high-density (2.82 g/cm<sup>3</sup>) Franciscan greenstones probably contribute to these gravity highs. The lowest gravity values, less than -14 mGal in Los Altos Hills up to about -5 mGal near Stanford University, are the northwestern-most expression of a large negative regional gravity anomaly called the Cupertino low (Robbins, 1971) that extends throughout the western Santa Clara Valley ground water basin (Department of Water Resources, 1975). Tertiary (pre-late Pliocene) sedimentary rocks and the Santa Clara Formation crop out in the Los Altos Hills. Considering that the Santa Clara Formation is less than 500 feet thick where exposed within the Palo Alto 7.5' quadrangle (Pampeyan, 1970), the high amplitude of the Cupertine low within the quadrangle implies that is caused primarily by the Tertiary sequence than the Santa Clara Formation. Using the Bouguer slab approximation, a thickness of about 6400 feet of Tertiary (pre-late Pliocene) rocks overlying the Franciscan assemblage would account for the 25 mGal difference between the gravity highs and lows. This is consistent with estimates by Pampeyan (1970) that the thickness of the Butano(?) Sandstone exceeds 3000 feet and that the maximum thickness of the unnamed sandstone of Miocene age and Monterey Formation are about 1500 feet and 1200 feet, respectively. All three of these rock units crop out in this area. The gravity "valley" that extends from Los Altos Hills and beyond Stanford University to Menlo Park is bounded on the southwest by a prominent gravity gradient that roughly parallels, but is well to the east, of the San Andreas fault. This gradient is caused by thinning of the Tertiary sequence toward the west and thrust faulting that has uplifted the Franciscan assemblage consisting mainly of dense greenstone. To the north, the gradient turns abruptly eastward, just south of Eagle Hill in Redwood City and turns gently back to a northwest trend near the Bayshore Freeway. Therefore, the Franciscan assemblage is probably continuous and at fairly shallow depth in Redwood City where residual gravity values are over +6 mGal. This relative gravity high continues northwestward through San Carlos to Belmont (Chapman and Bishop, 1968), where Franciscan rocks are again exposed (Brabb and

From the gravity high in Redwood City, a relative gravity high or "ridge" plunges southeastward through Atherton and Menlo Park with residual gravity values from +3 to -1 mGal. Several wells penetrate the Franciscan assemblage along this gravity ridge and to the northeast. This gravity ridge still remains af ter subtracting the gravitational effect of the alluvial deposits modeled in Sheet 3, indicating that it correlates with a block of relatively dense Franciscan rocks. The gravity ridge rapidly attenuates to the southeast, between Menlo Park and Palo Alto and continues southeastward, though less pronounced, through Palo Alto near Castilleja School and Bowden Park. The attenuation of the gravity ridge indicates that the block plunges or is downdropped to the southeast beneath the Santa Clara basin. Based on a clearly defined gravity gradient, the southwestern edge of the block probably abuts the Tertiary sequence on a near vertical fault contact in Menlo Park and Atherton (see Atherton fault, Sheet 3). In Menlo Park, the northeastern edge of this anomaly is bounded by a very linear gravity gradient, probably indicating a fault (see Redwood City fault zone, Sheet 3). An elongate magnetic high trending N 40° W coincides with the elongate gravity low located northeast of the gravity ridge. The gravity low is centered near Ravenswood School in East Palo Alto and extends northwesterly through the Menlo Park Sewage Disposal site (abandoned). Two-dimensional (2-D) gravity and magnetic modeling indicates that the magnetic anomaly and relative gravity low can be explained by a large, concealed serpentinite body

According to well descriptions, the alluvial deposits are at least 917 feet thick over the Franciscan assemblage (Table 1, Sheet 1, Brabb well no. 20) near San Fransquito Creek. Thus, by the Bouguer slab approximation, the alluvial deposits contribute as much as -6 mGal at this location. Further southeast, the alluvial deposits are as much as 1066 feet thick over the Tertiary sequence (Table 1, Sheet 1, Brabb well no. 33) near Barron Park in Palo Alto, which would contribute about -7 mGal relative to Franciscan rocks and -3 mGal relative to Tertiary (pre-late Pliocene) rocks. The anomalous gravity component depends on the reference density of the gravity model. Nevertheless, the Tertiary sequence contributes more (as much as -25 mGal) to the amplitude of the largest gravity lows, because the thickness of the Tertiary sequence is much greater than the thickness of the alluvial deposits. Where the Tertiary (pre-late Pliocene) rocks underlie the flatland deposits, the gravity anomalies are mainly caused by a combination of the two. However, the interface between the alluvial deposits and the Tertiary sequence is much shallower than the interface between the Tertiary sequence and the Franciscan assemblage. Thus, variations in thickness of the alluvial deposits will have more of an effect on short-wavelength gravity variations than variations in thickness of the Tertiary sequence. Therefore, some of the short-wavelength "wiggles" in the gravity contours over the flatland areas may be related to variations in the thickness of the alluvial deposits. Based on this premise, 3-D gravity modeling of the alluvial deposits was performed in order to determine the elevations of the bedrock surface (Sheet 3). Alternatively, the short-wavelength anomalies could be explained by variations in density within the alluvial deposits. A thickening of alluvial deposits would imply a buried valley or basin whereas the alternative explanation of decreased density would imply increased porosity. Regardless of thickness and/or density as an explanation, the short-wavelength gravity lows could still be considered

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# TABLE 1.-Rock density data for the Palo Alto 7.5' quadrangle

lithology	number of samples	average density $(g/cm^3)$	std. error (g/cm³)	range (g/cm³)
alluvial deposits	n. a. <sup>1</sup>	2.12	n. a.1	1.80-2.33
Tertiary sequence	88	2.36	n. a.1	1.59-2.99
Miocene sedimentary rocks	40	2.28	0.04	1.59-2.91
Page Mill Basalt	10	2.70	0.05	2.42-2.99
Eocene sedimentary rocks	38	2.44	0.03	1.90-2.67
Franciscan assemblage	71	2.67	n. a.1	2.08-3.40
graywacke	28	2.63	0.03	2.34-3.10
greenstone	13	2.82	0.04	2.49-3.06
serpentinite	10	2.47	0.12	2.08-3.40
chert	8	2.60	0.07	2.49 - 2.68
limestone	6	2.65	0.01	2.60-2.68
blueschist	6	2.98	0.03	2 90-3 08

<sup>1</sup>n. a. = not applicable